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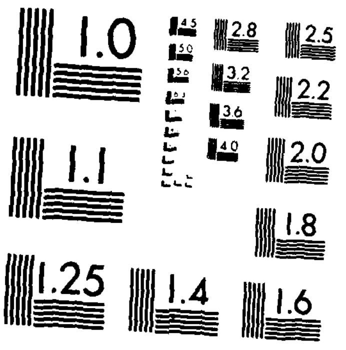

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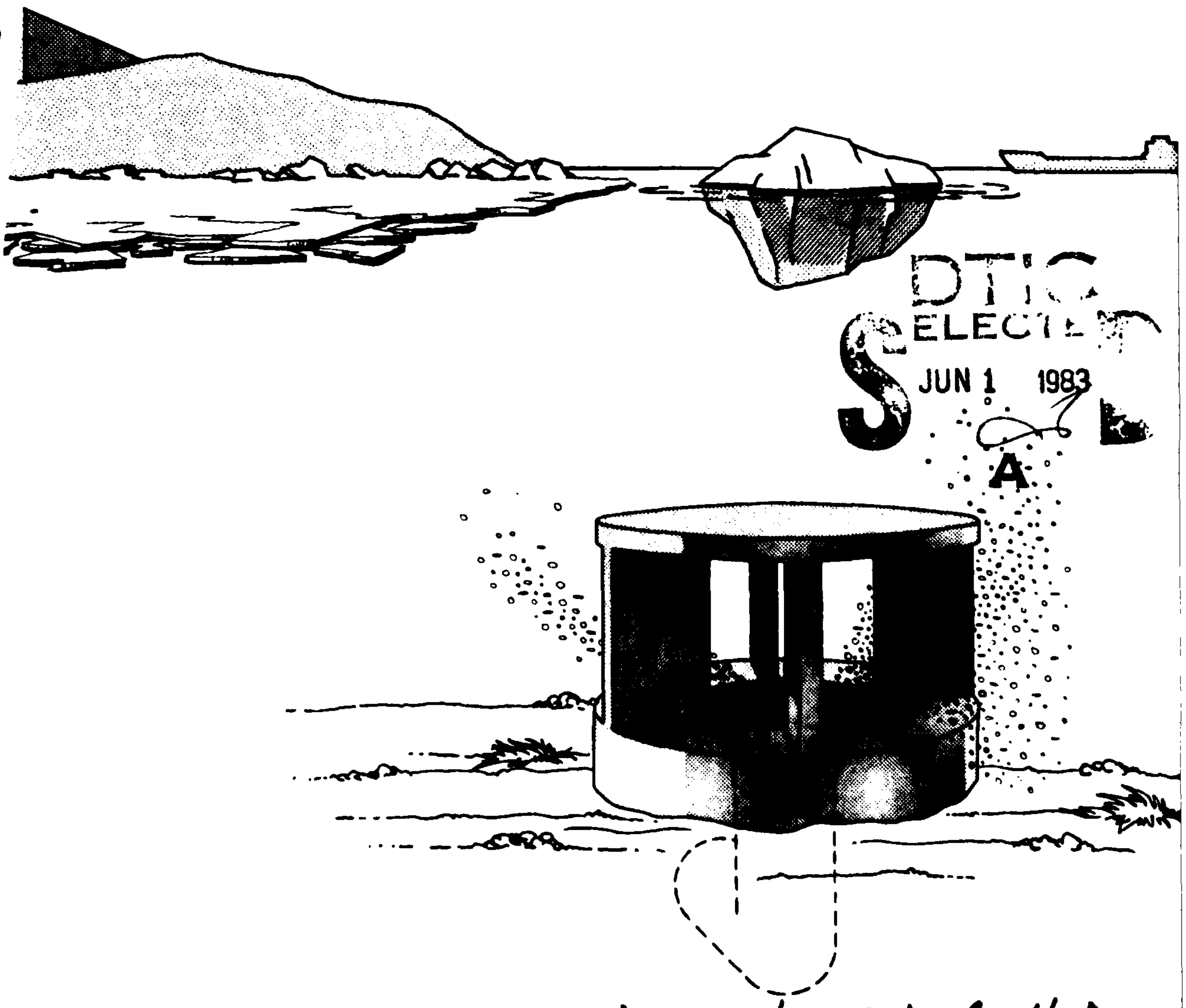

CRREL Report 83-15

May 1983

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Arnold M. Dean, Jr.

Prepared for
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CRREL Report 83-15	2. GOVT ACCESSION NO. AD-A128757	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LAKE WATER INTAKES UNDER ICING CONDITIONS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Arnold M. Dean, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31724
11. CONTROLLING OFFICE NAME AND ADDRESS Office of the Chief of Engineers Washington, D.C. 20314		12. REPORT DATE May 1983 13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ice
Ice prevention
Water intakes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An intake may be restricted or clogged by active frazil, passive frazil, brash, or a combination of these ice forms. The exact nature of the interactions among the intake structure, the ice and the hydraulic and meteorologic conditions that lead to icing problems is extremely site-specific. The better these parameters are quantified, the more tailored and economical the solution. A defense against these ice forms may be formulated in four areas: the origin of the ice, the transportation mechanics of the ice, the accumulation characteristics of the ice, and the form of the ice when it is in the area of influence of the intake.

To produce a lake intake structure that minimizes or eliminates icing problems, one may devise an unconstrained or a constrained design. To evaluate solutions to icing problems and/or to supplement incomplete data, a scale-model

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20. Abstract (cont'd).

investigation is recommended. A universal, unconstrained solution would be extremely expensive. The more data available through site monitoring and model studies, the better the problem (and therefore the solution) can be bracketed. This paper provides guidance for developing a site-specific solution.

PREFACE

This report was prepared by Arnold M. Dean, Jr., Electrical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, CRREL. It was funded under CWIS 31724, *Frazil Ice Control for Field Use.* The report was technically reviewed by Dr. George Ashton and James Wuebben of CRREL.

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A

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimetre
foot	0.3048*	metre

* Exact.

LAKE WATER INTAKES UNDER ICING CONDITIONS

Arnold M. Dean, Jr.

INTRODUCTION

The location of water intakes in lakes and rivers in northern areas makes them subject to icing problems, which may be severe. This report is concerned with investigating icing characteristics and constructing a strategy to cope with these problems in locations of low ambient flow velocities.

Site characteristics vary so widely that a general solution to intake icing problems would address all possible icing conditions at their greatest intensity; therefore, the closer that a particular site can be characterized, the more efficiently its icing problem can be solved.

The principles and techniques discussed here will guide in designing or modifying any intake structure. The defense may take the form of eliminating ice, diverting and managing ice, modifying ice characteristics, and/or minimizing structure-ice interactions. The extremes to which the defense must be taken is a function of the specific site. Limited site-specific data may be used to generate a risk analysis of the icing conditions, thereby forming a basis for design decisions.

This report results from an investigation of the types of icing problems that can occur at lake intakes. The purpose of the report is 1) to identify current techniques used to combat icing problems, 2) to discuss the basic principles applicable to combating lake intake icing problems, and 3) to apply the conclusions to a design approach for lake water intakes.

The literature and research review and evaluation covered the associated areas of ice nucleation, crystal growth, ice adhesion and cohesion, documentation and theory of the icing of water intakes, frazil ice, ice-hydraulic interactions and ice management. A selected bibliography covering these areas is at the end of this report.

ICING PROBLEMS AND PRESENT DEFENSIVE MEASURES

Surface ice may form from sheet ice, frazil conglomerates, brash ice, ice bergs or ice ridges. Additionally, sheet ice may be fast ice or floes, and frazil conglomerates may have a weak or strong structure.

Surface ice can reduce the heat transfer to the air, reducing the generation of ice at the origin; it can be an impediment to the transport of ice from the origin to the intake; or it can channelize the ice in transport and deliver it to the intake. If the structure of a submerged intake extends up to the water surface, surface ice may accumulate and deflect subsurface ice down to the intake.

Subsurface ice with which a water intake must contend includes active and passive frazil particles and conglomerates. These ice forms may also have a weak or strong structure, and may be distributed down to 50 or 60 feet (Alekseenko 1971, Giffen 1973). Active subsurface ice in the water column usually has a decreasing concentration with depth and is highly adhesive. The amount of accumulation depends on the heat transfer characteristics between the ice and the structure to which it is adhering.

Water intakes can be constricted by floe entrainment, floe and brash constriction, passive frazil constriction and stoppering, and active frazil constriction

(Alekseenko 1971, Michel 1971, Ahinikov et al. 1972, Giffen 1973, Foulds 1974, Wahanik and Fromuth 1976, Foulds and Wigle 1977).

Several techniques are being used to combat these problems. One approach is to place lake intake structures ad deep as possible and as far from shore as economics allow; this is based on the principle that such an area has the lowest concentration of active frazil ice. It has been qualitatively observed that intakes with smooth surfaces made from low-thermal-conductivity material have a better survival rate under icing conditions. Screen and trash rack element spacing varies from at least 2 inches to at least 2 feet. Occasionally racks are removed. Rack heating has been used extensively with varying degrees of success (Balanin 1970, Khovko 1971, Ahinikov et al. 1972, Giffen 1973, Hayes 1974, Logan 1974, Wahanik and Fromuth 1976, Gevay and Erith 1977). Other techniques include the use of steam jets (Williams 1959) and air jets (Bonnefille et al. 1971), groundwater mixing (Zakharov 1970), cooling water recirculation (Giffen 1973, Skarborn and Korol 1977, Carey 1979), the use of an electromechanical de-icing grid (Levin and Valin 1971), the generation of an ice cover (Pariset and Hausser 1961, Kanavin 1972) and the use of "ice-phobic" coatings (Piotrovich 1969). Additional structures such as booms, insulating covers and windscreens have been used, and instrumentation for forecasting frazil runs has been developed (Granbois 1953a, Arden and Wigle 1972).

DEFENSE EVALUATION

An effective defense may be engineered 1) at the ice origin by eliminating the ice, 2) in the intermediate region by using ice transport mechanics to divert and manage the ice, or 3) in the intake area by using ice accumulation mechanics to modify the ice characteristics or by altering the ice form by minimizing the interaction between the structure and the ice.

It is axiomatic that the success of the defensive measures is directly related to one's ability to describe the site characteristics. As soon as a site is seriously considered, a data accumulation program should begin. This program should include in-situ parameter monitoring and local interviews, and should produce a mathematical model that provides a risk assessment of icing conditions. The importance of such an investigation cannot be overestimated.

Ice origin

Ice is generated through sufficient heat transfer from the liquid water. Once the water column is cooled to about 0°C, the total volume and type of ice generated depends on the quantity and rate of the heat transfer. Surface disturbances such as wind and wave action increase the heat transfer by preventing the formation of a stable ice cover and applying a "wind chill" to the surface.

The higher the heat transfer rate from liquid water, the greater the probability of frazil ice generation. If sheet ice covers the water body, the heat transfer will never be such as to generate frazil ice; however, open water at about 0°C should be considered a potential frazil generator. The lower the below-freezing air temperature and the higher the surface turbulence and surface wind velocity, the more likely that frazil will form.

The water cooling rate about 0°C has given empirical, site-specific guidance in predicting the occurrence of frazil ice (Granbois 1953b, Arden and Wigle 1972). For the documented work the water cooling rate about 0°C was greater than or equal to 0.017°C/hr.

To prevent frazil from forming, the rate of heat transfer from the liquid water must be reduced. This may be done by growing an ice cover (Pariset and Hausser 1961, Kanavin 1972) or covering the area with a fabricated (insulating) cover (Williams 1959). If site characteristics do not allow this approach, then a defense in another area must be engineered.

Ice transport mechanics

From its origin the ice may be transported by strong prevailing winds, prevailing or periodically persistent currents, general surface turbulence or wave action, or undercurrents generated by the effect of the intake structure itself. In addition, frazil may have a vertical density profile associated with the vertical components of mixing and with its buoyancy (Michel 1971, Giffen 1973).

The goal of the defense in this area is to eliminate problem ice forms from the vicinity of the intake. Interrupting or modifying the transport mechanism that delivers ice to the water intake structure may provide an adequate defense to the icing problem. The transport mechanism may be affected by ice booms, surface covers, pilings (Brachtl 1974), breakwaters (Matousek 1974), deflection walls and screens (which may be vertical or horizontal) (Michel 1971, Tantillo 1981), or combinations of these structures.

Ice accumulation mechanics

Ice may accumulate by forced association (caused by flow patterns or winds), by the freezing of supercooled water among the particles (Michel 1971, Foulds and Wigle 1977), or by the application and release of sufficient pressure on the particulate mass for the required period of time (Colbeck 1976, 1978, Dean 1978).

Forced association may not necessarily make the ice mass more rigid; however, as compaction and ice concentration increase (without refreezing), the shear strength and bearing capacity will increase. The limit of this increase for average field frazil occurs when the ice concentration is about 60–70% by volume (Dean, in prep.), but the maximum value of this strength without refreezing is not known.

When the ice mass is buoyant enough to overcome the submerging effect of the flow, the water among the particles at the surface may freeze. Subsurface supercooling has been recorded and may account for conglomeration within the water column. Further, active frazil particles, which have at least a film of supercooled water about them, conglomerate when they come into contact within the water column (Michel 1963, Devik 1964, Alekseenko 1971, Giffen 1973, Foulds 1974).

The pressure application and release mechanism that forms a snowball may also account for the restructuring of porous ice masses. This may occur with the pressure differentials on clogged, submerged, intake screens and trash racks, resulting in consolidated ice masses with increased structural integrity and density (Kanavin 1972, Dean, in prep.). This mechanism should be quantified through a wide pressure range.

Ice accumulations may be mitigated by modifying the wind or flow patterns bringing the ice together, typically by mechanical or structural means. Instrumentation can be installed at the intake to monitor pressure drops or flow velocity, so that appropriate remedial actions may be taken.

Ice at the intake

The interaction among the intake, the intake flow and the ice in the range of influence of the intake determines the existence and the nature of an icing problem.

The ice may be active or passive. The active state, brought on by supercooled water about the particles, is characterized by the tendency of the ice to be highly adhesive and cohesive. Ice masses in the passive state may consolidate to block the intake (Logan 1974). Additionally passive ice under pressure may be restructured so that backflushing cannot remove the blockage (Colbeck 1976, Dean 1978).

The accumulation of active ice on a structure is driven by the tendency for the supercooled water about the ice to release its latent heat and change state (Williams 1967). The probability of accumulation is directly proportional to the entrained ice concentration, the temperature gradient between the ice and the structure (Devik 1964), the thermal conductivity of the structure (Michel 1963, Williams 1967, Giffen 1973), and the hydraulic smoothness of the surface (Michel 1963, Williams 1967, Piotrovich 1969). The hydraulic smoothness of the structure further implies that the probability of ice adhesion is also proportional to the probability and force of impact between the ice particle and the structure, and the amount of time that the particle is in contact with the structure. The thermal and hydraulic characteristics of the intake, then, help to describe the ability of, and probability for, the supercooled water about the ice particle to release its latent heat and to solidify between the ice particle and the intake structure.

Although only qualitative relationships are shown at present, the degree of supercooling and the duration of the supercooling periods greatly affect the ability of an intake to survive under active icing conditions (Williams 1967). Characterization of these site parameters can provide guidance for intake design and performance prediction. The spacing of, and material for, trash racks and screen elements, for instance, will depend on the degree and duration of supercooling. Only empirical site data can aid the designer in this area.

Short of mechanical removal, the ice form at the intake can be changed only by applying heat. One can, in the order of increased amount of energy required, 1) heat the surface of the structure to keep the ice from adhering, 2) heat (and mix) the water to reduce active frazil to passive, or 3) heat (and mix) the water to eliminate the ice. Since mixing a large water body is difficult, and the amount of heat necessary to eliminate the ice is great, the last is seldom considered. A compromise is usually attempted by mechanically removing the entrained passive frazil ice (for instance, with traveling screens).

DISCUSSION

The previous comments have emphasized the need to characterize the site and the potential icing problems. The better the thermal and hydraulic nature can be described, the more effective the defense will be. The weakest point in intake design for winter operation is a lack of information on and understanding of the site hydraulic and icing conditions. Site characterization may be obtained through 1) in-situ monitoring, 2) local interviews, and 3) data retrieval from organizations that monitor weather, hydraulic and icing conditions daily or periodically.

Design approaches

The present lack of understanding of the relationships among icing, hydraulic and structure parameters leads engineers to develop an unconstrained design, a constrained design or a scale-model investigation.

An unconstrained intake design is one that is purported to function under all icing conditions. This capability is determined by either considering all possible icing conditions that could occur anywhere or extrapolating from limited site data. As appropriate data become available, more realistic extrapolations can be made. Unless restricted icing conditions can be guaranteed, truly unconstrained designs are complicated and expensive undertakings.

A constrained design is based on limited data and applicable generic research guidance, and has an associated probability of successful performance under specified icing conditions. Lake intake design criteria will be discussed below.

A refrigerated model may be used to investigate the relationships among ice accumulation, hydraulic parameters and intake characteristics, and can be an extremely effective way to obtain data otherwise available only from full-scale field work. Models of selected parameters or isolated characteristics are often used as a supplement to describe unknowns in unconstrained or constrained designs.

Lake intake design criteria

Ice origin

At the ice origin the heat transfer from the liquid water should be minimized. This can be done by growing an ice cover, emplacing some form of surface insulation, or erecting structures such as wind shields or dikes.

Frazil ice cannot form below an ice cover; hence, completely covering the ice origin (however unlikely) would constitute an unconstrained design for frazil ice. If the ice origin is too large an area, then the intake should be displaced as far as possible from the origin. An ice or insulating cover can be grown, accumulated or placed at the surface over the intake. Its dimensions, usually a few hundred feet in diameter, must be calculated so as to render the active ice inactive when it reaches the intake. Since the ice concentration generally decreases with depth, the intake should be as deep as possible. While the intake is being installed, it would be wise to examine site water currents (to verify the entrained ice movement and density profile) and sediment transport (for potential entrainment problems).

Ice transport mechanics

In ice transport mechanics, potential defenses range from eliminating all ice (except a smooth continuous ice cover) from the vicinity of the intake structure to assuring that ice reaching the intake will cause only periodic problems. The elimination of all ice at the intake except a smooth ice cover would require an early ice cover and a giant circumferential filter. If such a filter were constructed, the openings would have to be smaller than active frazil particles (i.e. sub-millimeter). These openings would almost certainly be clogged by the active frazil. To minimize this, filter heating (discussed later) and backflushing would be required. Mechanical cleaning might also be necessary. Since entraining velocities for frazil particles are on the order of 0.01 ft/s (Osterkamp 1978), an intake of any typical flow would require a circumferential filter of inordinant size to minimize its attraction of frazil particles.

If one will accept a constrained design, the filter may be functionally approximated by trash racks, piles, dikes, ice booms, etc. The smaller the openings among these elements compared to the ice forms in the vicinity, the more likely that flow will be restricted. Likewise, the closer the elements of a rack or screen and the smaller the intake pipe diameter, the less likely that the structure can operate through extended frazil runs or supercooling periods.

Hydraulic conditions may be such as to allow the use of a deflector. For instance, if prevailing currents exist during frazil runs, the principle of momentum separation may be used. If the transport magnitude is adequate, the separation occurring at river bends between the water and the sediment or ice load would also provide a reasonably ice-free source of water for the intake. Further, if the flow component responsible for delivering the majority of the frazil to the intake can be identified, then it may be isolated and reduced at the intake. An example is the use of a "dealer's shade" horizontal plane above the intake (as a radially extended velocity cap) to reduce the vertical component of the flow; another example is the use of a partially or completely submerged circumferential wall to reduce the horizontal component of the flow.

Transport and accumulation mechanics

Transport and accumulation mechanics may combine to form a means of controlling the ice form at the intake. After an initial growth period, the frazil particles tend to conglomerate. The rate and extent of conglomeration is affected by the degree of turbulence. Should the currents and turbulence be reduced in the vicinity of the intake, the buoyancy of the conglomerates would tend to reduce the overall ice concentration and increase the ice concentration gradient in the water column. The larger the conglomerates, the less sensitive they are to the influence of the intake. This manipulation of the ice form may be effected by using the ice transport modification devices mentioned earlier (piles, dikes, ice booms, etc.).

Ice at the intake

Ice at the intake can be in the form of strong or weak conglomerates; in addition it may be active or passive frazil particles. A strong conglomerate is one that does not deform and pass through the intake. As mentioned earlier, active ice is cohesive and adhesive. An active, strong conglomerate may have been on the surface, exposed to subfreezing temperatures, and brought down to the intake through turbulence, wave action, etc. Strong conglomerates must be kept away from the intake or modified to pass through the intake. This may be done mechanically, thermally, or both, the exact design being site-specific. If passed through the intake, the conglomerates will accumulate elsewhere in the plant. The associated problem has not been eliminated, but has been transferred to another area, where it may be tolerated or handled more readily. Such a decision would likely be unique to each facility.

As discussed previously the accumulation of active frazil on a structure is a result of the tendency of its associated supercooled water to release its latent heat. To reduce the accumulation, the rate of heat transfer and/or the quantity of supercooled water must be reduced. To eliminate the accumulation the heat transfer and/or the supercooled water must be eliminated. The rate of heat transfer to the intake surface can be reduced by using material with low thermal conductivity or by designing the intake so as to minimize the amount and time of contact between the particle and the structure.

If the frazil or supercooling run is long enough, even a low thermally conductive material will cool enough to provide adequate heat transfer for the ice to begin accumulating. The accumulation will increase at a reduced rate until the thermal conductivity of the iced surface is no longer influenced by the structure's surface. At that point, accumulation will continue as if the surface were totally iced. Field and laboratory observations suggest that the lower the thermal conductivity, the later the initial accumulation and the lower the rate of accumulation during the initial period. Additionally the surface may be coated so that the strength of the bond between it and the ice is significantly reduced (Hanamoto 1977).

The heat transfer to the intake surface may be eliminated by heating the intake structure to a small fraction of a degree above freezing. Hence, any surface on which ice should not be allowed to accumulate must be heated; these include known areas of flow separation and screen and rack members.

Monitoring equipment for such applications is critical for operating economically and forecasting accurately. Generally, temperatures of the intake structure surface, the water, and the water near the surface at the ice origin should be monitored. The heat may be left off until the critical site-spec temperature and cooling rate are attained; th re generally in the range of a few tenths of a deg Celsius and about 0.02°C/hr, respectively.

Rack and screen heating, typically requirir)- 500 W per ft^2 of intake frontal area (for a 2- head), only eliminates active adhesion to the r ers and does not defend against conglomerates larger than the member spacing (Logan 1974). Because they are entrained by the intake flow, the conglomerates may completely clog the racks or screens; the ice may deform under the impact or pressure differential and become practically impermeable (Alekseenko 1971, Colbeck 1978, Dean 1978). If the ice is expected to grow or conglomerate to a size larger than the spaces in the members, racks or screens should not be used or should be removed each season.

Often one is tempted to resort to heating the incoming water, rather than the structure and rack or screen surfaces, in an attempt to reduce the active frazil to passive frazil. The extreme degree of mixing typically necessary makes this result practically unattainable under low flow conditions (Foulds 1974). This approach still does not eliminate the clogging that can be caused by ice masses.

CONCLUSIONS

Sheet, brash and frazil ice, and their conglomerates, affect lake water intakes. These ice forms are generated under adequate hydraulic and thermodynamic conditions, and are transported into the intake's area of influence. Combatant techniques are to reduce or eliminate 1) ice generation, 2) ice transport, or 3) ice entrainment or the effect of entrainment (clogging or stoppage).

Active frazil ice may exist to great depths. If practical, the generating area can be minimized. One may 1) attempt to accumulate the particles upstream of the intake, 2) design the intake so that the accumulation on the structure is minimized, or 3) accept the entrainment of frazil ice and deal with the consequences in the plant.

The accumulation of active or passive frazil ice over an intake screen or grating is sufficient to stop flow, as the mass will deform under loading to an extremely low porosity. An intake designed to avoid this problem and still have fixed screening has not been developed. Sheet and brash ice can usually be restricted from the intake area by barriers and/or deflections, since their density is usually not sufficient to reduce the availability of water. The application of heat in various forms has proven to be the only direct, effective defense against active frazil.

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Dean, Arnold M., Jr.
Lake water intakes under icing conditions / by Arnold M. Dean, Jr. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1983.
iv, 14 p., 28 cm. (CRREL Report 83-15.)
Prepared for Office of the Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory.
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